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The contribution of star-forming galaxies to the cosmic radio background

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ABSTRACT

Recent measurements of the temperature of the sky in the radio band, combined with literature data, have convincingly shown the existence of a cosmic radio background with an amplitude of ~ 1 K at 1 GHz and a spectral energy distribution that is well described by a power law with index $\alpha \simeq -0.6$. The origin of this signal remains elusive, and it has been speculated that it could be dominated by the contribution of star-forming galaxies at high redshift if the far infrared-radio correlation $q(z)$ evolved in time. We fit observational data from several different experiments by the relation $q(z) \simeq q_0 - \beta \log(1+z)$ with $q_0 = 2.783 \pm 0.024$ and $\beta = 0.705 \pm 0.081$ and estimate the total radio emission of the whole galaxy population at any given redshift from the cosmic star formation rate density at that redshift. It is found that star-forming galaxies can only account for ∼13 percent of the observed intensity of the cosmic radio background.

Key words: galaxies: emission – Star formation rate

1 INTRODUCTION

Although the detection of diffuse radio emission dates back to Jansky (1933), the origin of the cosmic radio background (CRB) is still a mystery. The recent data obtained by the Absolute Radiometer for Cosmology, Astrophysics and Diffuse Emission (ARCADE 2) has revived the interest in this question, detecting a diffuse background at frequencies between 3 and 10 GHz that is more then $5\,\sigma$ above the COBE/FIRAS measurement of the temperature of the cosmic microwave background (CMB) and well in excess of current estimates based on radio source counts. More precisely (Fixsen et al. 2011), the inferred value of the antenna temperature as a function of frequency can be expressed as

$$T(\nu) = \frac{h\nu/k}{\exp(h\nu/kT_{\rm CMB}) - 1} + T_{\rm R}\left(\frac{\nu}{\nu_0}\right)^{\alpha-2} \qquad (1)$$

where $T_{\rm CMB} = 2.729 \pm 0.004$ K denotes the thermodynamic temperature of the CMB, $T_{\rm R} = 1.19 \pm 0.14$ K is the normalization of the radio background at $\nu_0 = 1$ GHz, and $\alpha = -0.62 \pm 0.04$ is the spectral index of the CRB, consistent with synchrotron emission from normal galaxies (see e.g. Condon 1992).

The observed emission is most likely of extragalactic origin (Kogut et al. 2011), and several candidates have been considered by Singal et al. (2010). Radio source counts detected by current surveys, sensitive to flux densities above $S_{1.4\,\rm GHz} \gtrsim 10$ μJy, cannot explain more than ~ 10 per cent of the signal (Gervasi et al. 2008; Massardi et al. 2010; Vernstrom et al. 2011), and low-surface brightness sources missed by these surveys may contribute, at most, an additional 15 per cent. Diffuse emission in regions far from galaxies is ruled out due to the overproduction of X-rays and γ-rays, so the only possible explanation is that the cosmic radio background is dominated by faint sources below the threshold of 10 μJy (Singal et al. 2010).

According to Singal et al. (2010), radio supernovae make a negligible contribution, and radio-quiet quasars may be responsible for only a few per cent of the emission. Thermal bremsstrahlung from the hot gas in galaxy clusters has been shown to contribute about $0.01 - 0.02$ K at $\nu = 1$ GHz (see e.g. Ponente et al. 2011), and the most reasonable candidate to explain the bulk of the CRB seems to be the population of ordinary star-forming galaxies at high redshift.

Some authors (e.g. Oh 1999; Cooray & Furlanetto 2004) have tried to estimate the contribution of free-free emission from star-forming galaxies to the radio background by resorting to phenomenological prescriptions to relate halo mass and star formation activity at different redshifts. However, if the far infrared-radio correlation (FRC) observed for local galaxies holds at all redshifts, there must be a tight relation between the radio and infrared backgrounds (Haarsma & Partridge 1998; Dwek & Barker 2002). From the measured intensity of the latter, one concludes that the

contribution of star-forming galaxies must be of the order of $5-10$ per cent.

During the last years, the advances in infrared and submillimetric instrumentation have made it possible to investigate the evolution of the FRC over a large fraction of the age of the Universe, and several recent studies (e.g. Ivison et al. 2010a,b; Michałowski et al. 2010) suggest that the correlation is linear at all times, but the normalization is offset towards increasing radio loudness at high redshifts, boosting the expected signal from star-forming galaxies by a significant amount. In the present work, we make a quantitative estimate of the contribution of star-forming galaxies to the CRB. The prescription followed to assign radio luminosities as a function of the instantaneous star formation rate is detailed in Section 2. The evolution of the far infrared-radio correlation is discussed in Section 3, and the implications for the cosmic radio background are shown in Section 4. Our main conclusions are briefly summarized in Section 5.

2 RADIO EMISSION FROM INDIVIDUAL GALAXIES

In normal galaxies, radio emission is always associated to star formation (see e.g. Condon 1992). Young, massive stars produce intense ultraviolet radiation that ionizes the surrounding medium, and thermal bremsstrahlung from these free electrons (often referred to in the radio literature as *free-free* emission) makes a significant contribution to the galaxy spectra in the few-GHz range. On the other hand, stars with $M > 8\ \mathrm{M}_\odot$ explode as Type II and Type Ib supernovae at the end of their life cycle. Supernova remnants are thought to accelerate most of the relativistic electrons in normal galaxies, and they constitute the main source of the synchrotron emission that dominates at low frequencies.

Assuming a pure Hydrogen plasma with an electron temperature $T_\mathrm{e} \sim 10^4$ K, the free-free luminosity of a galaxy is approximately given by

$$\frac{L_\mathrm{ff}}{3.2\times10^{-39}\ \mathrm{erg\ s^{-1}\ Hz^{-1}}} \approx \left(\frac{\nu}{\mathrm{GHz}}\right)^{-0.1}\left(\frac{n_\mathrm{e}}{\mathrm{cm^{-3}}}\right)^2\left(\frac{V_\mathrm{e}}{\mathrm{cm^3}}\right) \quad (2)$$

where ν denotes the photon frequency, n_e is a characteristic electron density, and V_e represents the total volume occupied by the radio-emitting, ionized HII regions (Rubin 1968; Oh 1999). This volume is set by the condition that the number of ionizing photons Q emitted by the stars per unit time is equal to the recombination rate

$$Q = n_\mathrm{e}^2\ \alpha_\mathrm{B}\ V_\mathrm{e} \quad (3)$$

with $\alpha_\mathrm{B} = 2.6\times10^{-13}\ \mathrm{cm^3\ s^{-1}}$ being appropriate for case-B recombination at $T_\mathrm{e} \sim 10^4$ K. According to stellar population synthesis models (e.g. Leitherer & Heckman 1995; Mollá et al. 2009),

$$\frac{Q}{1.5\times10^{53}\ \mathrm{s^{-1}}} \approx \frac{\Psi}{\mathrm{M_\odot\ yr^{-1}}} \quad (4)$$

where Ψ is the current star formation rate (SFR) of the galaxy, assuming a Salpeter (1955) initial mass function (IMF) between 0.1 and 100 $\mathrm{M}_\odot$. In the end, the predicted free-free luminosity

$$\frac{L_\mathrm{ff}}{1.8\times10^{27}\ \mathrm{erg\ s^{-1}\ Hz^{-1}}} \approx \frac{\Psi}{\mathrm{M_\odot\ yr^{-1}}}\left(\frac{\nu}{\mathrm{GHz}}\right)^{-0.1} \quad (5)$$

scales roughly proportionally with the instantaneous star formation rate.

Computing the synchrotron luminosity from first physical principles is much more involved, since it requires knowledge of the amount of cosmic rays injected by supernovae, their spectrum, and the conditions of the surrounding medium (most notably, its density structure and the intensity of the magnetic field). Observationally (Condon 1992), non-thermal synchrotron emission is about 10 times more luminous than the free-free continuum at $\nu = 1$ GHz, and its spectral index is close to ~ 0.7 for a broad range of star-forming galaxies. In addition, there is a tight correlation between the synchrotron luminosity and the thermal radiation emitted by the dust in the infrared, which is powered by the stellar ultraviolet light and is thus another tracer of the star formation rate. The observed far infrared-radio correlation suggests (but see e.g. Lacki et al. 2010; Lacki & Thompson 2010, for a different point of view) that synchrotron emission is also proportional to the SFR, implying that

$$\frac{L_\mathrm{syn}}{1.8\times10^{28}\ \mathrm{erg\ s^{-1}\ Hz^{-1}}} \approx \frac{\Psi}{\mathrm{M_\odot\ yr^{-1}}}\left(\frac{\nu}{\mathrm{GHz}}\right)^{-0.7}. \quad (6)$$

3 EVOLUTION OF THE FRC

Since most of the contribution of normal galaxies to the cosmic radio background observed today is due to their synchrotron emission, with thermal bremsstrahlung (see e.g. Oh 1999; Seiffert et al. 2011; Ponente et al. 2011) providing only a minor correction at the level of a few percent, equation (6) has a crucial importance. In particular, the intensity of the CRB is extremely sensitive to the evolution in time of the relation between SFR and radio luminosity.

It is not clear, though, whether the far infrared-radio correlation should evolve with redshift, and current observational evidence is far from being conclusive. While several recent studies (e.g. Ibar et al. 2008; Sargent et al. 2010) are consistent with no evolution in the FRC, some others report systematic trends with redshift (e.g. Vlahakis et al. 2007; Beswick et al. 2008; Seymour et al. 2009; Michałowski et al. 2010).

The main source of uncertainty is that normal galaxies are rather faint in the radio band. According to equation (6), only the most intense starbursts, with instantaneous SFR in excess of $\Psi \gtrsim 30\ \mathrm{M}_\odot\ yr^{-1}$, would be detectable at $z \geqslant 1$ by current surveys, whose sensitivity at 1.4 GHz is of the order of $\sim 10\ \mu$Jy.

One possible solution (see e.g. Marsden et al. 2009; Pascale et al. 2009; Patanchon et al. 2009) is to stack the confusion-limited and sensitivity-limited radio images at the positions of thousands of infrared-selected galaxies. In doing so, one increases the signal-to-noise ratio and reduces the contribution of radio-loud active galactic nuclei (AGN), probing a population that is more representative of normal galaxies. This procedure has been applied by Ivison et al. (2010a) to a mid infrared-selected sample of galaxies, obtaining that

$$q \equiv \log\frac{L_\mathrm{IR}\,/\,3.75\times10^{12}\ \mathrm{W}}{L_{1.4\,\mathrm{GHz}}\,/\,\mathrm{W\ Hz^{-1}}} \propto (1+z)^\gamma \quad (7)$$

with $\gamma = -0.15 \pm 0.03$. Both the total infrared luminos-

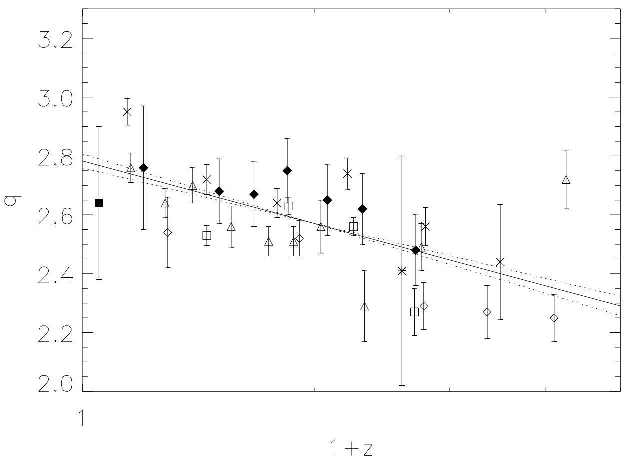

Figure 1. Evolution of the far infrared-radio correlation. Least-squares fit (solid line) with 1σ limits (dash lines) to the observational data from (Bell 2003, full squares), (Murphy et al. 2009, stars), (Michałowski et al. 2010, open diamonds), (Sargent et al. 2010, triangles), (Bourne et al. 2011, full diamonds), (Ivison et al. 2010a, crosses) and (Ivison et al. 2010b, open squares).

ity $L_{\rm IR}$ (defined from 8 to 1000 μm)[1] A similar analysis (Ivison et al. 2010b) is consistent with no evolution, $\gamma = -0.04 \pm 0.03$, but discarding the least reliable data at $z < 0.5$ yields $\gamma = -0.26 \pm 0.07$.

Alternatively, one may detect high-redshift star-forming galaxies by observing their rest-frame infrared dust emission, shifted towards sub-millimeter wavelengths. Based on a sample of 76 sub-millimeter galaxies with measurements in the radio band, Michałowski et al. (2010) conclude, in agreement with previous studies (e.g. Kovács et al. 2006; Murphy 2009) that the radio emission of high-redshift galaxies scales linearly with the SFR, but the normalization is about a factor of two higher than for local samples.

Although selection effects (see e.g. Sargent et al. 2010) and potential biases arising from spectral templates (Bourne et al. 2011) cannot be completely excluded, a combination of different data sets is fairly well reproduced by

$$q(z) = q_0 - \beta \log(1+z) \tag{8}$$

with $q_0 = 2.783 \pm 0.024$ and $\beta = 0.705 \pm 0.081$ (see Figure 1). Assuming that $L_{\rm IR} \propto \Psi$ and that the constant of proportionality does not vary with redshift, this implies that the synchrotron luminosity of a given galaxy scales as

$$\frac{L_{\rm syn}}{1.8\times10^{28}\ \rm erg\ s^{-1}\ Hz^{-1}} \approx \frac{\Psi}{\rm M_\odot\ yr^{-1}} \left(\frac{\nu}{\rm GHz}\right)^{-0.7} (1+z)^\beta \tag{9}$$

In other words, we assume that the infrared luminosity is an unbiased tracer of the SFR and that all the evolution of the FRC is due to the conversion between SFR and radio luminosity.

[1] The difference with e.g. the far-infrared band (from 60 to 100 μm) is about a factor of two. and the radio power $L_{1.4\,\rm GHz}$ are given at the rest-frame of the source, using a k-correction based on spectral templates.

4 THE COSMIC RADIO BACKGROUND

The specific intensity of the cosmic background at any given frequency is given by the integral along the line of sight

$$I_\nu = \frac{c}{4\pi H_0} \int_0^\infty \frac{\epsilon_{\nu'}(z)}{(1+z)\,E(z)}\,{\rm d}z \tag{10}$$

of the average emissivity per unit volume $\epsilon_{\nu'}$. In this formula, c and H_0 denote the speed of light and the Hubble constant, respectively,

$$E(z) = \sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_{\rm k}(1+z)^2 + \Omega_\Lambda} \tag{11}$$

reflects the cosmological expansion, and $\nu' = \nu(1+z)$ is the initial frequency at which the photons observed today with a frequency ν were emitted. We adopt a WMAP7 (seven-year observation) cosmology with $\Omega_{\rm m} = 0.27$, $\Omega_{\rm k} = 0$, $\Omega_\Lambda = 0.73$, and $H_0 = 71$ km s^{-1} Mpc^{-1} (Larson et al. 2011) and compute the brightness temperature of the CRB as

$$T(\nu) = \frac{c^2\, I_\nu}{2k\nu^2} \tag{12}$$

using the Rayleigh-Jeans approximation, where k is the Boltzmann constant.

By definition, the average emissivity at a given redshift is the sum

$$\epsilon_{\nu'}(z) = \int_0^\infty n(\Psi, z)\ L_{\nu'}(\Psi)\ {\rm d}\Psi \tag{13}$$

of the contributions of all the galaxies at that redshift, with $n(\Psi, z)$ representing the number density of galaxies with SFR between Ψ and $\Psi + {\rm d}\Psi$ at redshift z. As long as the relation between luminosity and instantaneous star formation rate is linear, $L_{\nu'} = \kappa(\nu', z)\,\Psi$, as indicated by equations (5) and (9), one can express the total emissivity

$$\epsilon_{\nu'}(z) = \kappa(\nu', z) \int_0^\infty n(\Psi, z)\ \Psi\ {\rm d}\Psi = \kappa(\nu', z)\ \dot\rho_*(z) \tag{14}$$

in terms of the cosmic SFR density $\dot\rho_*$ (Dwek & Barker 2002). The emissivity of the free-free and synchrotron components can be taken into account simultaneously as

$$\epsilon_{\nu'}(z) = \left[\kappa_{\rm ff}(\nu', z) + \kappa_{\rm syn}(\nu', z)\right]\ \dot\rho_*(z) \tag{15}$$

with

$$\frac{\kappa_{\rm ff}(\nu', z)}{1.8\times10^{27}\ \rm erg\,s^{-1}\,Hz^{-1}\,M_\odot^{-1}\,yr} = \left(\frac{\nu'}{\rm GHz}\right)^{-0.1} \tag{16}$$

and

$$\frac{\kappa_{\rm syn}(\nu', z)}{1.8\times10^{28}\ \rm erg\,s^{-1}\,Hz^{-1}\,M_\odot^{-1}\,yr} = \left(\frac{\nu'}{\rm GHz}\right)^{-0.7} (1+z)^\beta \tag{17}$$

where $\beta = 0$ for a non-evolving far infrared-radio correlation, and $\beta = 0.705 \pm 0.0801$ to fit the data plotted in Figure 1.

The evolution of the cosmic SFR density has been extensively studied during the last decade, and several compilations of observational data exist in the literature (e.g. Somerville et al. 2001; Ascasibar et al. 2002; Hopkins 2004; Hopkins & Beacom 2006; Michałowski et al. 2010). In the present work, we have adopted the parametrization of Cole et al. (2001)

$$\frac{\dot\rho_*(z)}{\rm M_\odot\ yr^{-1}\ Mpc^{-3}} = \frac{a+bz}{1+\left(\frac{z}{c}\right)^d} \tag{18}$$

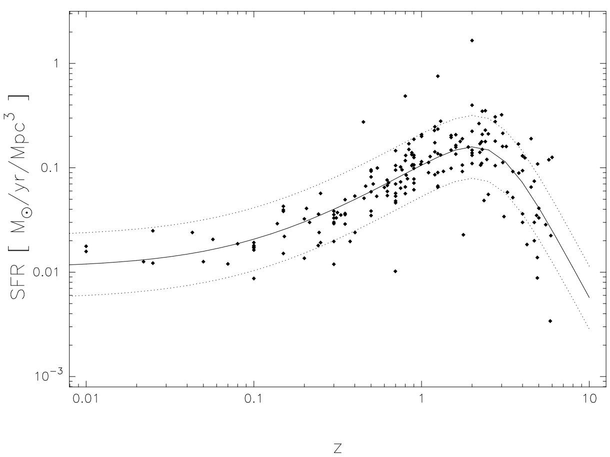

Figure 2. Cosmic star formation history. The solid line shows the best fit provided by expression (18) to the data points compiled by Michałowski et al. (2010), and dotted lines illustrate an uncertainty of a factor of 2.

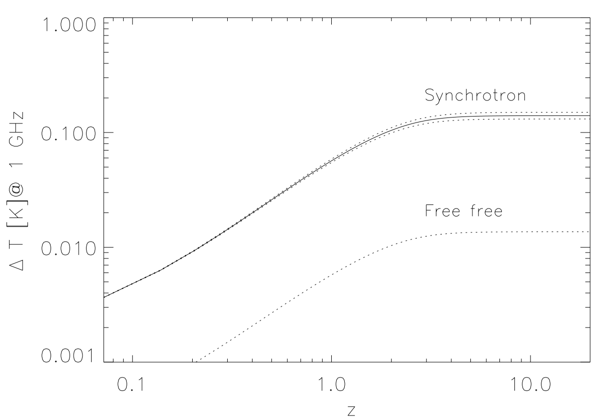

Figure 3. Integrated radio emission, observed at 1 GHz, from normal galaxies up to redshift z. ΔT refers to the excess signal above the CMB temperature. The solid line shows the contribution of synchrotron emission, assuming $\beta = 0.705$, and the errors associated to the least-squares fit (~ 0.01 at the end of the integration) are indicated by the dashed lines. The contribution of free-free emission is plotted as a dotted line.

and fit the observational data points reported in Table A.4 of Michałowski et al. (2010)[2]. The optimal values $(a, b, c, d) = (0.011, 0.097, 2.73, 3.96)$ have been obtained by means of the FiEstAS sampling technique (Ascasibar 2008), a Monte Carlo integration scheme based on the Field Estimator for Arbitrary Spaces (FiEstAS; Ascasibar & Binney 2005; Ascasibar 2010). The resulting cosmic star formation history is plotted as a solid line in Figure 2.

Combining expressions (10), (12), (14), (16), and (18), we estimate that the contribution of free-free emission from star-forming galaxies to the cosmic radio background is

$$\frac{T_{\rm ff}}{0.0137\ {\rm K}} = \left(\frac{\nu}{\rm GHz}\right)^{-2.1} \tag{19}$$

whereas, using expression (17), synchrotron emission yields

$$\frac{T_{\rm syn}}{0.0817\ {\rm K}} = \left(\frac{\nu}{\rm GHz}\right)^{-2.7} \tag{20}$$

for $\beta = 0$ and

$$\frac{T_{\rm syn}}{0.1402\ {\rm K}} = \left(\frac{\nu}{\rm GHz}\right)^{-2.7} \tag{21}$$

for $\beta = 0.705$. As can be seen in Figure 3, the signal is dominated by galaxies at $z < 3$, due to the combined effects of distance dimming and the declining behavior of the cosmic star formation rate at high redshift.

5 DISCUSSION AND CONCLUSIONS

In the present work, we have considered the relationship between the cosmic star formation rate and the radio background from star-forming galaxies in the light of recent measurements of the far infrared-radio correlation at different redshifts, attempting to give a further look into the significant missing flux that has been reported by the ARCADE2 team.

Our main result is that normal galaxies can *not* be responsible for the observed signal.

Although we think this conclusion is fairly robust, there is always some room for uncertainty. Radio emission in local galaxies has been thoroughly studied, and its properties are well known (see e.g. Condon 1992), but different gas compositions and/or temperatures may affect the conversion factor between SFR and radio emission by a significant amount, of the order of several tens of percent.

On the other hand, we use the cosmic star formation rate density to constrain the average emissivity of the universe (Dwek & Barker 2002). In contrast to radio source counts, where a population of faint objects below the detection threshold is very difficult to rule out (Singal et al. 2010; Vernstrom et al. 2011), it would be extremely unlikely that our proposed fit underestimates the average SFR by more than a factor of two (dotted lines in Figure 2). Uncertainties in the IMF cancel out with the production rate of ionizing photons given by expression (4) and are not expected to affect the present analysis significantly.

The most important source of uncertainty is the possible evolution of the far infrared-radio correlation. Current observations seem to be compatible with $\beta = 0.705 \pm 0.081$, increasing the expected emission from normal galaxies by about 70 per cent with respect to the case of no evolution. Using an extreme value $\beta = 1$ would boost the signal by only an additional 35 percent.

Nonetheless, it is worth noting that the high-redshift points in Figure 1 (e.g. in the samples of Michałowski et al. 2010; Murphy et al. 2009) are dominated by sub-millimeter galaxies. There is some discussion in the literature that these sources, whose contribution to the total SFR at $z \sim 1-2$ is only of the order of ten per cent (see Figure 4 in Michałowski et al. 2010), may be radio-bright compared to normal galaxies and introduce some evolution in the observed FRC that does not apply to star formation as a

[2] Conversion to a Salpeter IMF between 0.1 and 100$M_\odot$ and a WMAP7 cosmology (following the prescription in Ascasibar et al. 2002) amounts to a negligible correction.

whole[3]. In fact, one would expect on theoretical grounds that the FRC of normal galaxies evolved in the opposite direction ($\beta < 0$). On the one hand, star formation at $z \sim 1$ is heavily obscured by dust, and the approximation that all the ultraviolet luminosity is re-radiated in the infrared is very good. In the local universe, some fraction of the ionizing photons is able to escape, and the infrared luminosity per unit SFR should be lower. On the other hand, galaxies at high redshift should produce less radio emission because the energy density of the CMB scales as $(1+z)^4$, and the relativistic electrons injected by supernovae lose more energy through inverse Compton scattering (see e.g. Carilli & Yun 1999; Carilli et al. 2008; Murphy et al. 2009). Both effects, especially the latter, would only strengthen our conclusions, and the estimate with $\beta = 0.705$ should arguably be regarded as an upper limit.

According to our results, radio emission from star-forming galaxies could explain up to $\sim$ 13 per cent of the intensity of the CRB. Even taking all the possible uncertainties into account, we are still far from the 1.19 Kelvin reported by ARCADE2 at 1 GHz. Although evolution of the FRC at $z < 3$ has to be further investigated, current data strongly suggest that it only results in a relatively minor boost to the contribution of normal galaxies, and hence we can rule them out as the main source for the radio background. As shown in Figure 3, the contribution of galaxies at higher redshifts is negligible.

Since relatively bright point sources, as well as Galactic or extragalactic diffuse emission have also been ruled out (Singal et al. 2010, and references therein), there are few alternatives left to explain the observed cosmic radio background. Some possibilities are:

(i) The ARCADE2 measurement is incorrect, or it is contaminated by Galactic foregrounds. Being perfectly consistent with independent measurements at longer wavelengths (e.g. Haslam et al. 1982; de Oliveira-Costa et al. 2008; Rogers & Bowman 2008), we think this possibility is unlikely.

(ii) Faint star-forming galaxies at high redshift are extremely radio bright, perhaps due to an enhanced magnetic field or AGN activity with respect to the brightest objects at that redshift (the possibility favored by Singal et al. 2010).

(iii) There is a new population of numerous and faint radio sources waiting to be discovered.

To sum up, the nature of the cosmic radio background poses an exciting challenge for radio astronomy, to be faced in the upcoming era of Expanded Very Large Array (EVLA) and Square Kilometre Array (SKA).

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[3] Just by removing the Michałowski et al. (2010) data from the least-squares fit, the best value of β decreases to 0.57 ± 0.093. Furthermore, the data at $z < 1$ are compatible with $\beta = 0$ (see the discussion in Sargent et al. 2010).

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